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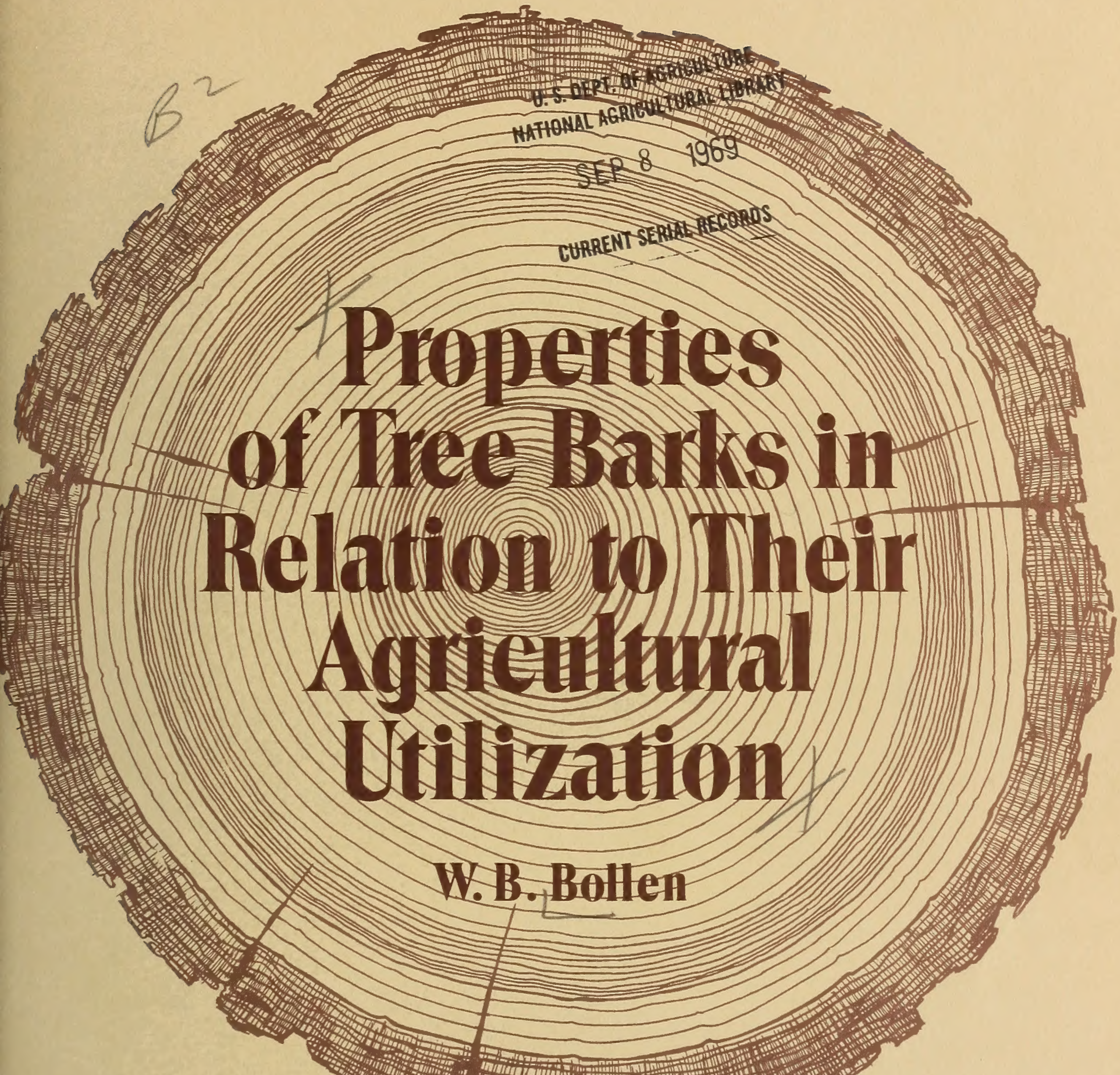

Properties of Tree Barks in Relation to Their Agricultural Utilization

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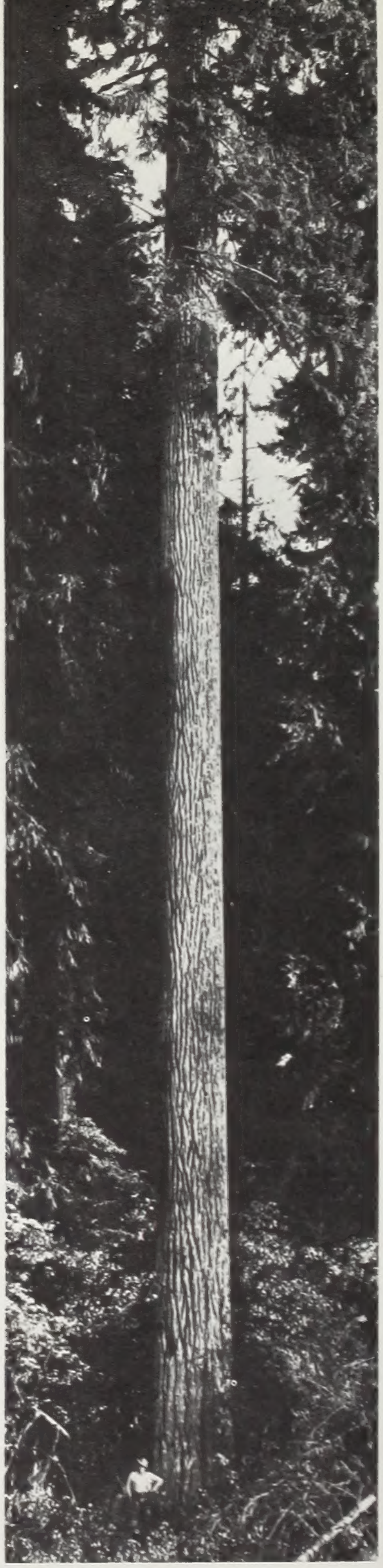

A mature, old-growth Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, the species from which most of the bark in the Pacific Northwest is derived.

Contents

Introduction

About 5 million tons of tree bark were produced in 1966 as "waste" from the Pacific Northwest wood products industry, more than two-thirds of which (table 1) came from Oregon and Washington.[1] If all this bark were to be concentrated in one place, the resulting pile would cover 1 square mile to a depth of 10 feet.

Other regions also produce large amounts of bark. The British Columbia lumber industry in 1963 produced 116 million cubic feet or about 1.5 million tons of bark, of which 48 percent was Douglas-fir, 22 percent was western hemlock, and the remaining 30 percent was from all other commercial tree species.[2]

Bark of major tree species of the Pacific Northwest constitutes a sizable portion of the log:

Tree species	Percent of gross log volume in bark
Douglas-fir (*Pseudotsuga menziesii*)	
Old growth	12-15
Young growth	8
Redwood (*Sequoia sempervirens*)	20
Ponderosa pine (*Pinus ponderosa*)	12
True firs (*Abies* spp.)	11
Western redcedar (*Thuja plicata*)	10
Western hemlock (*Tsuga heterophylla*)	8
Spruce (*Picea* spp.)	7

Tree bark has relatively little economic use at present, so disposal of this material poses a major industrial problem. In some cases, bark is buried in trenches or landfills. However, most mills dispose of their bark by burning, either for fuel or in wigwam burners. The smoke and particulate fallout thus created is a significant source of air pollution and a critical problem in areas of mill concentrations.

Federal laws require all States to enact pollution control measures. The Oregon Sanitary Authority has developed standards for water and air quality control which are being enforced within the limits of present day technology. The State of Washington is also developing such standards.

We urgently need to develop economic uses for bark to help solve a critical problem in the Pacific Northwest (Mater 1967).[3] This need will become greater, not only because of current and pending air pollution regulations but also because of high stumpage prices calling for maximum utilization of every part of the log (Cruickshank 1968).

In some localities, as much as 10 percent of the bark available is used in agriculture. A conservative estimate of bark so utilized in the Pacific States is about 100,000 tons per year.[4]

The amount of moss peat[5] marketed annually in the United States is approximately

[1] *Estimates of bark production were made from 1966 production of lumber and plywood. The Pacific Northwest, for purposes of this paper, includes Oregon, Washington, Idaho, western Montana, and northern California.*

[2] *Personal communication from Mr. E. Kerbes, Forest Products Laboratory, Vancouver, B.C. 1968.*

[3] *Names and dates in parentheses refer to Literature Cited, p. 32.*

[4] *From replies to a questionnaire sent in 1968 to county extension agents and sawmills.*

[5] *Moss peat, often incorrectly called "peat moss," is derived from mosses, usually species of* Sphagnum *or* Hypnum, *which undergo only partial decomposition in bogs and marshes because of lack of dissolved oxygen (Dachnowski-Stokes 1931). The arrested decomposition of this submerged organic material results in the formation and accumulation of "peat." Dried and shredded peat is marketed as "peat moss," although actually it is a peat derived from moss (Dachnowski-Stokes 1931, Schreiner and Shorey 1909). Dried, undecomposed sphagnum moss is also available as a medium for plant propagation by seed or cuttings. It is sterile and is prized for its property of inhibiting damping-off fungi (Creech et al. 1955).*

Table 1. — Estimated annual production of bark in Oregon and Washington, by species and log volume, 1966[1]

Species	Log volume	Bark per M bd. ft., log scale	Total bark	
	Billion bd. ft.	Cubic feet	Million cu. ft.	Tons[2]
Douglas-fir	8.20	20.0	164	2,510,000
Hemlock	1.84	12.5	23	328,000
Ponderosa pine	1.65	18.0	30	290,000
True firs	1.20	17.0	20	220,000
Redcedar	.40	15.0	6	69,000
Spruce	.18	11.0	2	20,000
Total			245	3,437,000

[1] *Estimate by Pacific Northwest Forest & Range Experiment Station, Portland.*

[2] *75 percent water content, ovendry basis.*

500,000 tons (Sheridan and De Carlo 1957). Bark could replace much of this material.

The possibilities for using large quantities of bark in agriculture are greater than might first be imagined. One encouraging development is use of waste bark as a replacement for the great amounts of sawdust and other fine wood wastes used in the past for mulches, soil conditioners, animal bedding, etc.

Sawdust, wood shavings, and chips are now in strong demand for pulping purposes in the Pacific Northwest. Some of the material is shipped to Japan, but most is consumed in the domestic market. County extension agents point to the growing scarcity of sawdust and shavings for farm use and call for more research on bark as a replacement material.[6] Another indication of the increasing demand for agricultural grades of bark is the growing number of mills and dealers now advertising such products for sale. Some representative prices for unamended bark are:

Portland, Oregon: Douglas-fir and hemlock bark, $15 per unit (200 cubic feet) delivered within city limits;

Medford, Oregon: Douglas-fir and white fir, $5 per unit, wholesale at the mill;

Corvallis, Oregon: Hemlock bark, $1 per 2-cubic-foot bag; Douglas-fir bark, $0.80 to $1 per 2½-cubic-foot bag; spruce bark, $3.50 per cubic yard in bulk at a local nursery; hemlock and Douglas-fir bark mixed, in bulk, $15 per unit delivered; and

California: Amended pine and white fir bark, $3 per 3-cubic-foot bag; in bulk, $7 to $14 per cubic yard, according to delivery distance.

The time is ripe to solve the troublesome problem of waste bark disposal with its attendant contribution to air pollution. In this paper, we shall discuss the possibilities for use of large volumes of bark for agricultural purposes and summarize our knowledge of the various properties of bark having a direct bearing on its use.

[6] *See footnote 4.*

Preparing bark for agricultural use

Bark is mechanically removed from logs by variously designed cutter heads, scrapers, or hydraulic debarkers which direct high pressure jets of water against the log. After this process, bark is ground in a hog mill or hammer mill, then screen-sorted into size ranges appropriate for the intended use. Water content of bark varies with the debarking method used and whether the log had previously been stored in water. Some drying, accomplished by allowing the bark to heat spontaneously in deep piles, may be necessary to obtain satisfactory grinding and screening. On the other hand, wet grinding would reduce dust and give a more fibrous product. Slotted screens effectively remove many wood slivers which detract from appearance of the bark.

Further processing — composting, ammoniation, pelletizing, or adding fertilizers and pesticides — may follow to enhance the value of bark. Stabilization, or satisfying the nitrogen demand of the microbial population, is often included as an additional feature. Rarely, however, are barks sufficiently fortified with plant nutrients to be considered fertilizers.

Ash (mineral) content is generally greatest in tree leaves or needles followed in order by that in bark, branches, and wood (Anonymous [n. d.], Lutz and Chandler 1946) (table 2). Bark has almost no plant nutrient value (tables 2 and 3), although in most cases bark nutrient content is higher than that of sawdust. Nitrogen content is very low. Ash is also

Table 2. — Some chemical characteristics of Douglas-fir bark, wood, and needles compared with alfalfa hay and wheat straw

(In percent, ovendry basis)

Chemical characteristic	Bark	Sapwood	Heartwood	Needles	Alfalfa hay	Wheat straw
Total carbon	53.97	49.36	51.51	55.75	43.15	44.70
Kjeldahl N	.11	.09	.12	.96	2.34	.12
C/N ratio[1]	491:1	548:1	429:1	58:1	18:1	373:1
Hot-water extractives	2.50	2.70	4.20	12.10	16.90	5.00
Cold-water extractives:						
Total	1.90	1.00	4.80	22.00	23.10	7.80
Reducing sugars	.79	.14	.77	5.65	2.70	3.98
Kjeldahl N	.04	.09	.13	.16	1.13	.48
C/N ratio[2]	1,250:1	556:1	385:1	313:1	44:1	104:1
Ash	.50	.30	.30	5.60	8.80	8.50
Alcohol extractives	13.70	3.50	8.10	36.60	15.70	8.00
Alcohol-benzene extractives	.20	.10	.30	.30	.60	.40
Holo-cellulose	42.20[3]	52.20	60.60	20.50	29.80	62.90
Klason lignin	41.60[3]	37.40	25.90	20.30	14.30	13.50
Crude protein	.70	.60	.80	6.00	14.60	.80

[1] *Not expressed as percent.*

[2] *Approximate: based on C = 50 percent.*

[3] *Not typical wood cellulose or lignin.*

Table 3. — Major plant nutrients in bark, sawdust, and moss peat

(In percent, dry basis)

Material	N	P	K	Ca	Mg
Bark:					
Douglas-fir	0.12	0.011	0.11	0.52	0.01
Ponderosa pine	.12	.003	.11	.25	.01
Redwood	.11	.011	.06	.29	.00
Red alder[1]	.73	.153	.24	1.25	.18
Sawdust:					
Douglas-fir	.04	.006	.09	.12	.01
Ponderosa pine	.04	.008	.12	.16	.02
Redwood	.07	.001	.01	.20	.02
Red alder	.37	.013	.12	.18	.04
Moss peat	.83	.030	.02	.50	.12

[1] Alnus rubra *Bong.*

low, but calcium is relatively high compared with other minerals. Phosphorus concentration is much less than that of nitrogen but is higher in bark of Douglas-fir and redwood than that of other tree species.

Nutrient content of bark differs not only with species but also with age of tree, environmental factors, and growing site. Bark content, especially of minor or "trace" elements, varies with the location in which the tree was grown (Ellis 1959, 1965). The amount of mineral elements in bark often reflects differences in availability of the element in soil rather than the amount necessary to satisfy nutritional needs of the tree.

In table 2, some chemical properties of Douglas-fir bark are compared with those of Douglas-fir wood and needles and with two agricultural residues commonly incorporated with soil — alfalfa hay and wheat straw. Douglas-fir bark contains more ash, alcohol extractives, and lignins than wood of the same species. Douglas-fir needles are notably higher than the wood in ash, sugars, and nitrogen. Alfalfa hay and wheat straw are also higher in the properties measured than is Douglas-fir bark or wood and thus more susceptible to rapid decomposition. Cold-water extractives are much higher in needles, alfalfa hay, and wheat straw than in bark or wood. These extractives represent water soluble constituents that would exert most of the immediate demand for nitrogen after being leached from bark into the soil by rain or irrigation. Before reaching the soil, some of these water soluble materials would probably undergo some decomposition in the bark itself by indigenous microbes and thus would not use nitrogen in the soil.

Ammoniation

Ammoniation, a relatively new process, is one way in which bark can be fortified with nitrogen which, as we shall see, is vital to the successful use of bark on or in the soil. Due to the presence of polyphenols, bark is highly acid and readily absorbs ammonia when wet. Spraying ground bark with aqua ammonia can add about 2 percent nitrogen (Bollen and Glennie 1963), more than is required for the complete microbial decomposition of bark over 6 to 10 years. Nitrogen, assimilated by microbes in early stages of organic matter decomposition, is released upon their death and becomes available for subsequent organisms attacking the more resistant residues.

Exposing Douglas-fir bark to anhydrous ammonia in a closed screw conveyor system

readily added 4 percent nitrogen in experiments conducted by Aspitarte[7] and Bollen and Glennie (1963). In a much simpler process, anhydrous ammonia gas is admitted through perforated pipes at the bottom of a 5-foot-deep bark pile covered with polyethylene sheets (fig. 1). Ammoniated bark is much darker than raw bark (fig. 1).

Bark must be wet for ammoniation to be effective. Portions of the pile near the points of gas admission become darker and more highly ammoniated. For a uniform product, the pile must be turned and allowed to cure after treatment, permitting equal distribution of the added nitrogen and escape of any free ammonia which might otherwise volatilize from the product when used as a mulch. An excess of ammonia could also cause too high a pH in the mulch or soil which could injure some plants.

A total nitrogen content of about 2 percent is obtained by ammoniation. Bark so treated, sometimes called stabilized or composted bark, has a pleasing dark color. Bollerslev (1968) describes a successful commercial operation wherein the best product is produced by composting ammoniated bark at 135° to 150° F. for approximately 90 days.

Ammoniation also softens the needlelike bast fibers of Douglas-fir so that they lose much of their objectionable handling properties. Ammoniated or otherwise fortified bark products should be positively labeled; otherwise, users may add nitrogen fertilizer and cause undesirable growth effects on plants.

Cork and fine bark fractions absorb more ammonia with longer exposure, but they absorb it differentially. Ricard[8] found that Douglas-fir bark fibers treated with anhydrous ammonia at room temperature and atmospheric pressure had a nitrogen content of about 3 percent. For the cork fraction, the value was 5.5 percent and for fines, 7 percent.

Half of the nitrogen introduced into Douglas-fir bark by ammoniation is not readily available to plants or to ammonifying organisms and is only slowly nitrified (Bollen and Glennie 1963). This slowly available portion of the nitrogen provides a reserve for subsequent demands by succeeding crops and against nitrification and possible loss of nitrate by leaching. Much of the nitrogen introduced by treatment with nitric acid or urea likewise is only slowly available. Bremner and Shaw (1957) found that nitrogen in nitrated pine sawdust was mineralized much more slowly than nitrogen in nitrated lignin. Lignin ammonia reaction products also decomposed less rapidly than nitrated lignin. More of the total nitrogen in nitrated sawdust is attached to the cellulose than to the lignin. Similar results would probably be found with bark whose major components are cellulose and lignin (table 2).

Composting[9]

Composting speeds the recycling of nutrients and stabilizes bark while overcoming its nitrogen deficiency. In the composting

Figure 1. — Ammoniated bark darkened in comparison with untreated bark.

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[7]*Aspitarte, T. R. Availability of nitrogen in ammoniated bark used as a soil amendment. 1959. (Unpublished Ph.D. thesis on file at Oregon State Univ., Corvallis.)*

[8]*Personal communication from Dr. J. L. Ricard, Forest Research Laboratory, Oregon State University. 1968.*

[9]*A bibliography with abstracts on "Sawdust and Bark for Composting and Mulching," covering the literature for 1949-67, is available from the Commonwealth Bureau of Soils, Harpenden, England. Of 78 publications reviewed, 14 deal with bark. A more recent, larger "Bibliography of Wood Waste Composts," by Seiji Uemura is available (in English) from the Ministry of Agriculture and Forestry, Government Forest Experiment Station, Meguro, Tokyo, Japan. These references and further Japanese research are discussed in detail (in Japanese) in an accompanying 271-page booklet, "Ringyo-Kairyo-Fukyu-Sosho" (translated title "Wood Waste Compost Manufacture and Applications").*

Figure 2. — Fermented center of large sawdust pile.

process, organic residues undergo sufficient decomposition to narrow the C:N ratio, much of the carbon passing off as carbon dioxide. The action should be allowed to proceed to near humification where some nitrogen becomes available as ammonium or nitrate. Materials of wide C:N ratio require addition of nitrogen fertilizers or readily decomposable nitrogenous wastes. Calcium cyanamid is a useful adjunct because, in addition to supplying nitrogen, it neutralizes acidity arising from fermentation and promotes microbial activity.

Combining fresh vegetable refuse with bark not only supplies additional nitrogen to the material but increases the composting action by hastening development of an active microbial population. Manure or sewage sludge may also be used in combination with bark. Watering and turning the pile controls the moisture, aeration, and temperature. Gessel (1959) and Macdonald and Dunn (1953) found that composted bark was superior to composted sawdust in promoting growth of cabbage in pot tests. Wood residues composted with poultry manure and rice bran have been found to depress many plant pests, apparently because the compost contains an abundance of antibiotic-producing microbes such as *Trichoderma* and *Streptomyces*.[10]

Composted wood residues provide intangible growth-promoting substances as well as available plant nutrients so they command premium prices. The darker color imparted by composting, especially of sawdust which is much lighter colored than bark, is an attractive feature.[11] Composts also have the capacity to counteract toxicities of biocides (Mader 1960).

Composted bark can be produced at a profit where raw materials and facilities for their processing are available. Some lumber mills in California have composted bark on a large scale. Ivory and Field (1959) point to a big market for composted bark; they also emphasize that the inherent qualities of bark produce a good compost and that special bacteria need not be introduced. Dost (1965) has mentioned composting of bark from pine and true fir species. A few Oregon mills and fuel dealers also market raw and composted bark (fig. 3). Such processing, however, is not likely to be undertaken by a mill which produces large quantities of bark that could be supplied to another enterprise willing to undertake the risks involved.

[10] *Personal communication from Dr. Seiji Uemura, Government Forest Experiment Station, Meguro, Tokyo, Japan. 1968.*

[11] Warning: *Raw sawdust that has darkened due to spontaneous heating by fermentation and subsequent chemical action in large compacted piles (fig. 2) is strongly acid and should not be applied to the soil (Bollen and Lu 1966). As much as 300 pounds of limestone may be required to neutralize 1 ton of such sour sawdust, dry basis. The acid, mainly acetic, imparts a pungent and irritating odor, which should warn against its use. Raw bark is susceptible to a similar fermentation.*

Figure 3. — Loamite and different brands of bark marketed in Oregon.

Decomposition and fate of bark in soil

Bark is a complex physical and chemical mixture of many organic compounds, mainly lignocelluloses and extractives, as shown in the following tabulation:

Structural components:

- Carbohydrates
  - Holocelluloses
  - Hemicelluloses
  - Galactans
  - Mannans
  - Glucosans
  - Arabans
  - Uronic acids
- Lignin
- Cork
  - Suberic acid
  - Suberin
  - Cutose
  - Quercitin
  - Dihydroquercitin

Nonstructural components:

- Coloring matter
- Tannins and related condensed tannins
- Polysaccharides, glucosides, sugars, and gums
- Volatile acids and oils
- Nonvolatile fatty oils and steroids
  - Higher alcohols
  - Resins
  - Hydrocarbons
  - Polyphenols
- Miscellaneous organic materials
- Ash (minerals)

These compounds are attacked differentially by a wide variety of microbes during decomposition or mineralization. All the physical, chemical, and biological reactions and interreactions between bark and soil are controlled by factors of environment, including water, temperature, aeration, pH, nutrients, and biological influences. Optimum conditions for desirable microbial activities are:

1. Moisture near field capacity or 50 percent of the water-holding capacity;
2. Temperature near 80° F.;
3. Aeration that occurs when water supply is near optimum;
4. pH close to neutral;
5. Nutrient supply balanced;
6. A carbon:nitrogen ratio approximating 25:1 for readily decomposable substances;
7. An active microbial population, especially in the vicinity of the root rhizosphere (Bollen 1959).

Extreme environmental conditions are inhibiting or toxic to microbes, but ranges over which microbial activities take place are quite wide. Important physical, chemical, and biological properties of barks, which vary with species and origin and influence their effects on and in the soil, are listed below:

Physical:

- Color
- Particle size distribution
- Structure
- Specific gravity
- Bulk density
- Water-holding capacity

Chemical:

- Proximate analysis
  - Carbohydrates
  - Fats
  - Protein
  - Ash
- Ligno-celluloses
- Phenolics and other extractives
- Carbon/nitrogen ratio
- Mineral elements

Biological:

- Age of tree from which bark was derived
- Site on which tree was grown
- Cork and bast
- Contaminants

Size of particles and their distribution influence surface-to-volume ratios and interspatial properties.[12] These factors must be considered in interpreting physical, chemical, and biological effects of materials added to soil. Rate of decomposition of red alder and Douglas-fir wood particles, ranging from approximately 0.002 to 2 millimeters, was found to increase as surface exposure increased (Neal et al. 1965) (fig. 4). Douglas-fir decomposed slower than red alder.

Shape of particles is also important. Surface-to-volume ratios change more rapidly with spherical than with cylindrical shapes; materials that yield granular particles, such as red alder and spruce barks, will exhibit certain properties more than hemlock or cedar bark screened through the same mesh size because many of the particles of the latter are elongate. Although Allison (1965) found that -6 mesh pine wood decomposed about as rapidly as a finer grind, this may have been because ground pine and some other ground woods contain many slivers.

Differences in chemical composition of plant sample fractions resulting from grinding and screening may also affect rates of decomposition. Smith et al. (1968) found the percentage composition of N, P, Ca, Mg, and SiO_2 in wheat straw, barley straw, alfalfa, and corn leaves generally increased as particle size decreased from 20 mesh to 100 mesh.

Water-soluble constituents of bark are most rapidly consumed by microbes, exert most of the nitrogen demand, and require none of the more specialized bacteria that consume cellulose and ligninlike material. Few kinds of microbes are now known to utilize lignin. These organisms include some higher fungi, *Fomes annosus* and other white rot basidiomycetes, and the *Streptomyces*, a group of moldlike higher bacteria. *Trichoderma lignorum* is one of the few species of common soil molds that attack lignin. Only recently have some true bacteria been shown to act on lignin and ligninlike substances; these include certain species of *Agrobacterium*, *Pseudomonas*, and *Mycobacterium* (Sundman 1961, 1964a, 1964b). However, a wider variety of microbes may be involved in lignin decomposition in the soil (Sundman et al. 1964). Although lignin is highly resistant, it is decomposed almost completely by the specialized microbes under aerobic conditions, the chief end products being carbon dioxide, water, and microbial cells. Bacteria, because of their great abundance in the soil and their most extensive surface area which reflects biochemical activity, could well play a significant role in degrading lignin to humus.

Much is unknown about the chemical and physical nature of native lignin, especially bark lignin. It is closely associated with cellulose, either as an encrustant or by chemical bonding (Pew 1967). In either case, lignification protects the cellulose against cellulolytic

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[12] *Mesh dimensions (square openings) of Tyler standard sieves:*

Mesh designation	Mm.	Mesh designation	Mm.	Mesh designation	Mm.
6	*3.36*	*60*	*0.250*	*200*	*0.074*
9	*2.00*	*100*	*.149*	*250*	*.063*
10	*1.68*	*170*	*.088*	*325*	*.044*
16	*1.000*			*400*	*.037*

Only spherical particles just passing through the screens would have the exact dimensions indicated. Irregular pieces could be smaller or larger in volume. Slivers especially, because of their tendency to "dive" through the openings, present more bulk and surface than do blunt particles of the same mesh size.

All material passing a given mesh is indicated by a minus (−) sign; material retained on the mesh is indicated by a plus (+) sign. Thus, -6 shows that all passed through; -10+40 indicates material passing through 10 mesh but retained on 40 mesh.

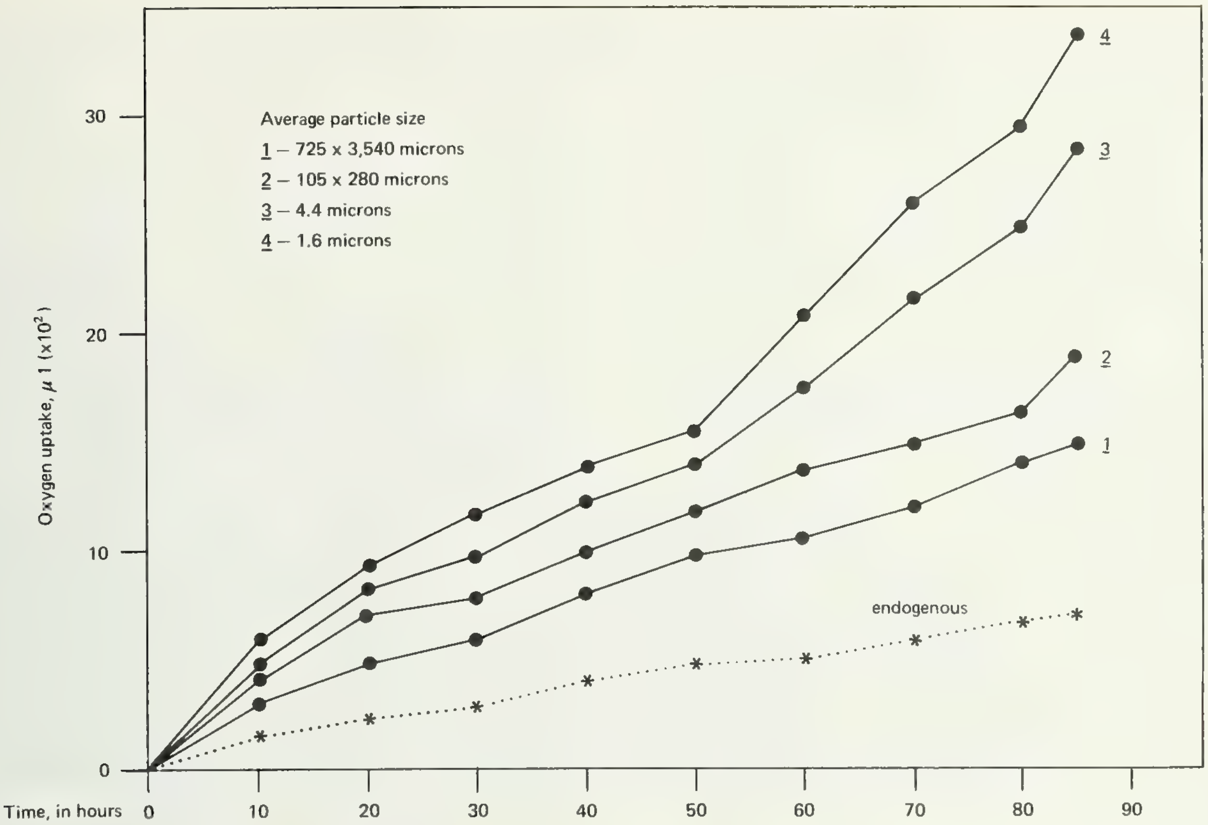

Figure 4. — Relation of particle size to rate of decomposition.

organisms and isolated enzymes. Certain microbes attack the lignin and thus expose the cellulose to attack by other organisms. Lignin metabolizers generally act slowly; this, with the cellulose-protecting role of lignin, accounts for the slow decomposition and low nitrogen demand for most bark and wood substance added to the soil.

Figures 5 and 6 show generalized courses of the reactions taking place when organic matter is decomposed or mineralized. Aerobic reactions, which take place in the presence of free oxygen, are more complete and more desirable in the soil than are anaerobic transformations. Anaerobic conditions in soil are induced by excessive water and also, at least

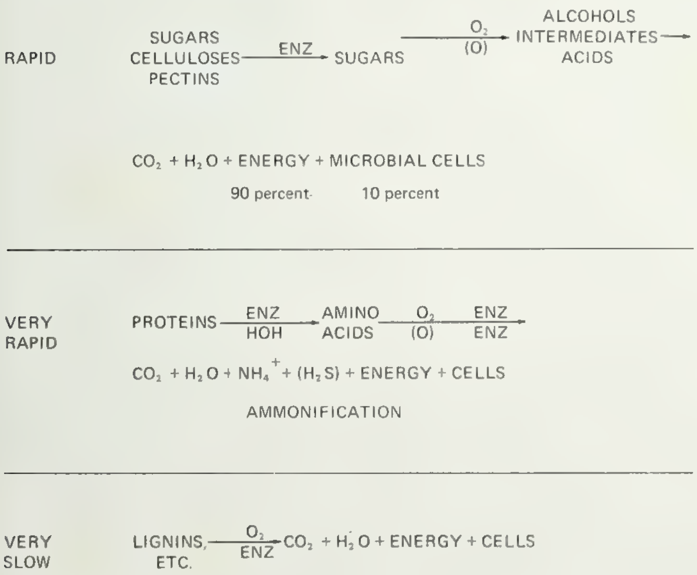

Figure 5. — Microbial decomposition of organic matter constituents.

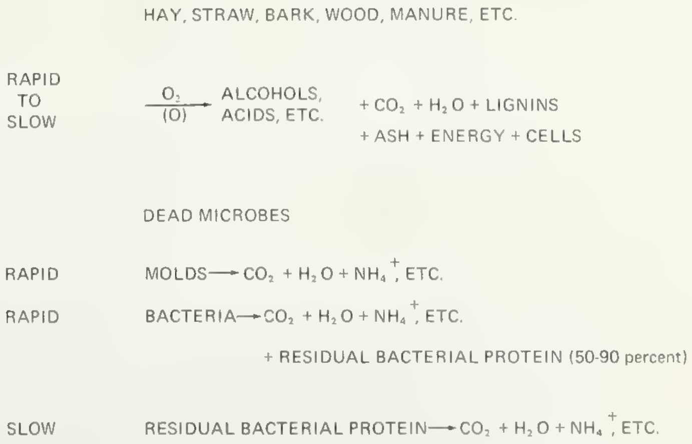

Figure 6. — Microbial decomposition of complex organic matter.

in microclimates within the soil, whenever a fresh addition of organic matter causes competition for free oxygen. Eventually, however, products of anaerobiosis will be oxidized whenever free oxygen becomes available.

Under favorable conditions, bark decomposes most rapidly during the first few days of exposure to microbial activity (Allison 1965, Bollen and Glennie 1961). Old-growth Douglas-fir bark decomposes more slowly than young-growth bark; ammoniated bark and moss peat are quite resistant to decomposition (table 4).

Laboratory studies by Allison (1965) on the decomposition in soil of -6 mesh woods and barks from 28 species of trees showed that during 60 days only two barks, those from incense-cedar (*Libocedrus decurrens*) and eastern redcedar (*Juniperus virginiana*) were oxidized more rapidly than the corresponding wood (table 5). Of 19 softwood species, the wood from shortleaf pine (*Pinus echinata*) decomposed most rapidly and that from eastern redcedar decomposed slowest; bark from lodgepole pine (*Pinus contorta*) decomposed most rapidly, redwood bark least rapidly. The mean value for the woods was 12.8 percent; for the barks, 8.8 percent. Over periods up to 800 days, however, decomposition of the woods ranged from 35 to 65 percent whereas for bark the range was 21 to 55 percent. Wheat straw decomposes much faster (Bollen and Glennie 1961).

The soil used in Allison's experiment supplied sufficient nitrogen for a maximum rate of decomposition of the barks and woods. Added sources of nitrogen in many cases decreased CO_2 evolution. Although this phenomenon is not uncommon when mineral nitrogen fertilizers are added with organic matter (Bollen and Glennie 1961, Bollen and Lu 1957), no adequate explanation has been

Table 4. — Decomposition of bark, wood, and other organic materials in silt loam soil incubated at 28° C. and 50 percent of water-holding capacity[1]

Material	Carbon released as CO_2 in 50 days: Bark	Carbon released as CO_2 in 50 days: Wood
	Percent	*Percent*
Douglas-fir:		
Young growth	26	30
Old growth	18	--
Ammoniated (2.83 percent N)[2]	5	--
Red alder	18	40
Western hemlock	16	27
Ponderosa pine	21	33
Western redcedar	8	33
Dextrose[3]	58	
Wheat straw[3]	48	
Moss peat	4	

[1] *–60 mesh materials incorporated with soil at 2,000 p.p.m. carbon. Data from Bollen and Glennie (1961) and Bollen and Lu (1957).*

[2] *T. R. Aspitarte (see text footnote 7).*

[3] *Standards for comparison.*

offered. Even with physiologically acid sources such as ammonium sulfate, the addition of some form of lime to ensure a favorable pH does not always increase the total CO_2 evolution. Possibly the added nitrogen relieves the soil microbes from obtaining their requirements by decomposing humus or other native organic nitrogen material, accordingly reducing the overall output of CO_2.

Differences in rates of bark decomposition between data presented in tables 4 and 5 are attributed to differences in particle size of organic materials used in the two studies, soil types, and experimental techniques. However, results of our studies (Bollen and Glennie 1961) indicated generally that bark of commercially important western tree species decomposes more slowly than corresponding wood.

Figure 7 illustrates the importance of the carbon:nitrogen ratio, and why nutrient nitrogen must be added to highly carbonaceous materials so that microbes involved in the decomposition will not seriously compete with plant roots for their nitrogen requirements. To a lesser degree, this is also true for phosphorus and sulfur.

C/N RATIO:

1. N < 1 PERCENT, C/N > 50. STRAW, BARK, WOOD. N INSUFFICIENT FOR MICROBES, WHICH ASSIMILATE NH_4^+, NO_3^-, OR AMINO ACIDS FROM SOIL. LASTING N STARVATION OF PLANTS. ADD N FERTILIZER

2. N < 2-2.5 PERCENT, C/N > 20-25. OAT, CLOVER HAY, ETC. TEMPORARY N STARVATION. NH_4^+ LIBERATED AFTER PRELIMINARY DECOMPOSITION.

3. N > 2-2.5 PERCENT, C/N < 20-25. ALFALFA, YOUNG NONLEGUMES, COTTONSEED MEAL, UREA, ETC. N IN EXCESS OF MICROBE REQUIREMENTS; NH_4^+ LIBERATED.

Figure 7. — Nitrogen relationships in organic matter decomposition.

Table 5. — Decomposition of - 6 mesh wood and bark at 100 tons per acre in Branchville sandy loam soil[1]

Material	Carbon released as CO_2 in 60 days	
	Wood	Bark
	Percent	
Douglas-fir	11.2	10.6
Eastern hemlock *(Tsuga canadensis)*	7.5	6.1
Ponderosa pine	13.7	9.6
White pine *(Pinus strobus)*	16.4	3.6
White fir *(Abies concolor)*	16.2	10.4
Eastern redcedar	1.5	17.7
Incense-cedar	4.2	6.5
Redwood	3.8	2.1
Mean of 19 softwoods	12.8	8.8
Black walnut *(Juglans nigra)*	27.1	13.7
White oak *(Quercus alba)*	38.1	27.4
Wheat straw	54.6	

[1] *After Allison (1965).*

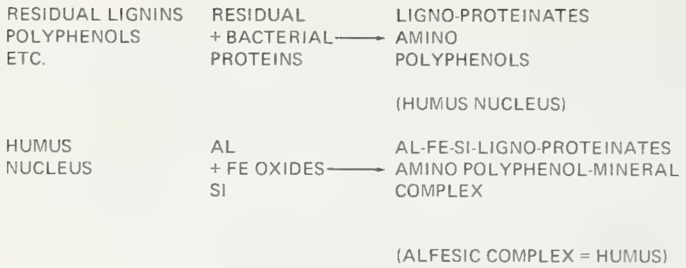

Figure 8. — Humus formation.

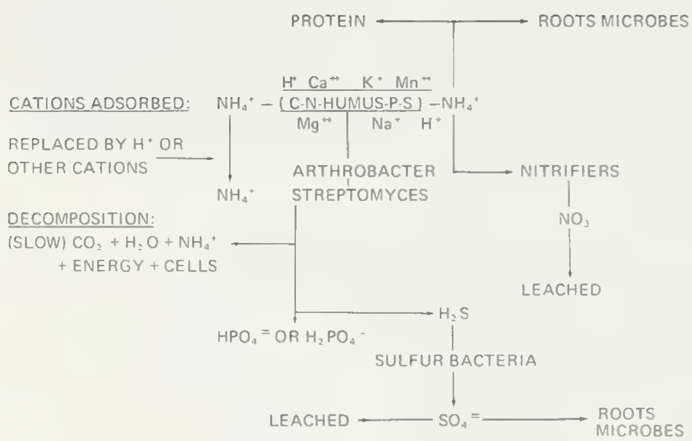

Figure 9. — Humus CEC and decomposition.

1. ALFALFA, DRIED BLOOD, PEPTONE, UREA, ETC.: C/N < 2-15. RAPIDLY DECOMPOSED. NH_4^+ LIBERATED
2. HUMUS, UF RESINS, LEATHER: N > 5 PERCENT, C/N < 0.5-10. DECOMPOSITION AND LIBERATION OF NH_4^+ SLOW, REGARDLESS OF N.

Figure 10. — Physical and chemical structure of organic matter in relation to N content and microbial decomposition.

Although different species of soil microbes have different quantitative requirements for food, the nutrient elements most extensively consumed in overall metabolism, other than oxygen and hydrogen, are carbon, nitrogen, phosphorus, potassium, and sulfur. Potassium is usually available in sufficient supply. The C:N:P:S ratios of total nutrients required by bacteria are approximately 50:1:0.5:0.1; i.e., for 50 parts C assimilated, 1 part N, 0.5 part P, and 0.1 part S are required for the overall metabolism. Soil nitrogen is most often a limiting nutrient in plant growth, and sometimes phosphorus and sulfur may also be deficient. With organic matter additions, therefore, supplemental phosphorus and sulfur should be considered in connection with soil type and kinds of plants to be grown.

Resistant lignins, resistant proteins, or other amino complexes of dead bacterial cells remain after the more susceptible components or organic matter additions have been decomposed. These residues combine with polyphenols to form a humus nucleus which absorbs iron, aluminum, and silicon oxides and becomes the complex known as humus or, as termed by Mattson (1948) (fig. 8), the Alfesic complex.

Humus, essential for soil tilth and fertility, represents a store of combined and sorbed nutrients. Typically, the C:N ratio is about 10:1. Nitrogen is slowly but continuously rendered available as ammonium by *Streptomyces* and specialized bacteria capable of attacking the resistant complex (fig. 9). Some of the soil nitrogen is in amino form, much of which in soil organic matter is not readily nitrifiable (Gupta and Reuszer 1961).

A high percentage of nitrogen in an organic material does not necessarily indicate it may be readily decomposed by microbes. Leather and urea-formaldehyde resins, as well as humus, have narrow C:N ratios, but their chemical or physical structure imparts high resistance to decay (fig. 10).

Effect of bark on plant growth

A former belief that tannins, resins, and other wood extractives have a toxic effect on plants when wood residues are added to soil has been found largely erroneous. We have learned from research that any "toxicity" noted after bark or other wood products are used on or in soil is most likely due to a nitrogen deficiency that can easily be remedied by adequate fertilization.

Extensive use of large proportions of various kinds of bark in container mixes for growing ornamental plants (Baker 1957, McNeilan 1967) attests to its favorable effects on plant growth. When adequate nutrients are supplied, especially nitrogen, plant growth in soil to which bark has been added is generally better than in corresponding unamended soil[13] (Bollen and Glennie 1961, Bollen and Lu 1957, Dunn 1956) (fig. 11, table 6). Yields were decreased without available nitrogen. Bark with added ammonium nitrate gave plant yields similar to those from unamended soil, but these were much less than from soil plus ammonium nitrate only. This finding emphasizes the assimilation of available nitrogen by microbes attacking the bark or wood.

In Willamette silty clay loam soil, Aspitarte[14] found that hot-water-extracted, Douglas-fir bark tannin liquor equivalent to 2,000 p.p.m. carbon was 33 percent decomposed in 60 days. On the same carbon basis,

[13] *See footnote 7.*

[14] *See footnote 7.*

Table 6. — Effect of bark, soil, and wood (sawdust) on yield of sunflowers on Willamette silt loam soil[1]

Treatment	Nitrogen content	C/N ratio	Yield (dry weight) average of three crops
	Percent		*Grams*
Soil only	0.16	16:1	84
Soil + NH_4NO_3 at 500 p.p.m. N	.21	12:1	109
Bark:			
Douglas-fir alone	.18	297:1	67
Douglas-fir + N	2.60	20:1	116
Douglas-fir composted	.25	221:1	86
Hemlock alone	.17	323:1	72
Hemlock + N	2.62	20:1	87
Wood (sawdust):			
Douglas-fir alone	.06	843:1	50
Douglas-fir + N	5.20	10:1	77
Hemlock alone	.06	841:1	54
Hemlock + N	5.20	10:1	75

[1] *1,500 grams soil per pot in greenhouse. Three replications. Organic additions at 10 tons per acre. N as NH_4NO_3.*

Figure 11. — Effect of bark and sawdust on growth of sunflower plants.

decomposition of wax amounted to 17 percent whereas only 8.5 percent of -20 mesh cork was decomposed.

Certain plant pathogenic fungi are inhibited and finally killed by tannin added to culture media (Cook 1911), probably by tanning the pectolytic enzymes (Williams 1963). Fungal mycelia are more tolerant than spores of the organism. Saprophytic fungi are less sensitive, and low concentrations of tannin appear stimulating, possibly serving as food. *Aspergillus niger*, a common soil mold, can thrive on tannin and has been used commercially to hydrolyze tannin to gallic acid (May and Herrick 1934).

According to Koch and Oelsner (1916), tannin is readily assimilated by soil molds, thus increasing the demand for ammonium and nitrate. Pine resin also was found to be utilized as an energy source. Tannin imparts a dark color to the soil, and large amounts harden the soil, presumably by precipitating colloids.

Certain cellulolytic bacteria are inhibited by tannins at 100 to 1,000 p.p.m., but the growth of others, except for changes in morphology, is only slightly affected (Henin et al. 1964). Shrikhande (1940) observed that fermentation of tea refuse was not impeded by the tannin complex, but the decomposition was qualitatively altered by selective action on the microflora. Plant virus transmission is inhibited by tannin, probably by action on the virus nucleoprotein (Cadman 1960).

Dihydroquercitin (Taxifolin), a flavonoid, occurs in bark and wood. In Douglas-fir bark, it amounts to as much as 8 percent of total dry weight, and in some Douglas-fir cork, it is more than 20 percent (Kurth 1951, 1953). Dihydroquercitin is believed to offer some decay resistance in lumber (Kennedy 1956) but is nontoxic to a wide variety of microbes and higher organisms.[15] Although small inhibition zones were found around crystals of the flavone placed on nutrient agar plates seeded with *Bacillus subtilis*, *Escherichia coli*, and *Staphylococcus aureus*, no toxicity was indicated by the phenol coefficient method.[16] At the same time, it was not utilizable by microbes as a carbon source.

Bark on the lower stem of Douglas-fir trees in moist locations is populated with numerous saprophytic molds to which the cork is resistant. Bark from ponded logs harbors many bacteria and other microbes. Freshly milled bark, unless completely dry, readily undergoes fermentation that generates heat; in large, self-insulated piles, this action may induce spontaneous combustion, as with sawdust. Extreme acidity also may develop.[17]

In laboratory experiments, finely ground bark decomposes rapidly in soil. For such studies, however, the bark is finely ground, usually -10 or -60 mesh, to allow intimate mixing with the soil sample. Surface exposure increases rapidly and microbial attack is facilitated as particle size is decreased. Allison (1965) found that during the first 30 days after soil treated with sawdust was exposed to microbial action, CO_2 evolution increased significantly with fineness of division of the particles. Thereafter, the differences between samples of -6, 10-20, and 20-40 mesh were within experimental error.

Regardless of mesh size, the screened product contains an assortment of particles ranging down to fine dust which will react most rapidly (fig. 4) (Neal et al. 1965). Results of decomposition studies must be interpreted with this fact in mind.

Bark is highly complex, physically as well as chemically. Douglas-fir bark, ground to pass 16 mesh, can be mechanically separated into the following percentages of different fractions: cork, -16+35 mesh, 25 percent; bast, -35+170 mesh, 25 percent; -170 mesh, fines and dust, 50 percent, consisting of broken cork and bast plus parenchyma and sieve cells. These components are decomposed in soil at different rates; -60 mesh cork was found to decompose more rapidly than bast or -60 mesh whole bark (Bollen and Glennie 1961). Less CO_2 evolved from the extracted young bark, suggesting a greater decomposability of the extractives. The water-extracted, old bark gave slightly more CO_2 than the unextracted, possibly indicating a

[15] *Personal communication from Dr. Harvey Aft, Forest Research Laboratory, Oregon State University.*

[16] *Bollen, W. B. Unpublished data. 1957.*

[17] *See footnote 11.*

water-soluble inhibitor. Of the mechanical fractions, the cork (-60 mesh) decomposed most rapidly, followed in order by bast (-35+170 mesh), fines (-170+250 mesh), and dust (-250 mesh). Larger particles(> -10 mesh) would decompose more slowly.

Gibbs and Werkman (1922) found that various sawdusts, incorporated at 100 to 300 tons per acre, slightly inhibited ammonification and nitrification in several different soils. All the sawdusts, except cedar, exerted very little inhibiting action on fixation of nitrogen in solution by *Azotobacter* (Gibbs and Batchelor 1928). Laboratory results have shown little retardation of ammonification and nitrification of peptone by Douglas-fir bark at 100 tons per acre, but nitrification of ammonium sulfate was inhibited (tables 7 and 8).

Water-soluble phytotoxins are produced under relatively high moisture conditions during decomposition of straw and other crop residues in soil (Toussoun et al. 1968). The phytotoxic effects of phenolics, which appear to be major components, decline after a few weeks. Similar soil toxins were recognized and extracted from soils many years ago (Schreiner and Shorey 1909). Fortunately, under aerobic conditions many soil organisms rapidly decompose such compounds (Gardner 1926). Bark is more resistant to decomposition than most other agricultural crop residues and should not be a serious source of phytotoxins, especially under anaerobiosis.

In climates where low temperature limits organic-matter decomposition, even when moisture is plentiful, soils of recently cleared coniferous timberlands may contain accumulations of toxic resins or pitch during the first few years of cultivation (Neidig and Snyder 1929). However, such accumulations do not occur in climates, such as that of western Oregon and Washington, where temperature and moisture are favorable to microbial action. Under optimum environmental conditions, finely divided Douglas-fir pitch is decomposed in soil as rapidly as straw (Bollen and Lu 1957) and pine resin also decomposes readily (May and Herrick 1934).

Bark decomposes slightly more slowly than sawdust. The bast fraction of bark is more resistant to decay than the cork fraction which contains tannins, dihydroquercitin, and other extractives that, by their nature, might be considered to be more or less toxic (Bollen 1959, Bollen and Glennie 1961). Glycosidal substances from bark of *Fraxinus* species have been reported to inhibit *Bacillus cereus* in vitro (Jung and Hubbes 1965). It is unlikely, however, that such inhibition would occur in soil, because antibiotics generally are susceptible to destruction by many soil organisms.

Tannins, plant polyphenols commonly used to convert animal skins to leather, range from 8 to 18 percent in Douglas-fir bark (Kurth et al. 1948, Kurth 1953). Tannin concentrations are highest in top logs of trees 50 to 80 years old. Bark from true firs contains comparable percentages but in mountain hemlock (*Tsuga mertensiana*), tannin concentration may be more than 20 percent (Kurth 1958). The following values have been reported for other species on the basis of 80-percent leaching efficiency: ponderosa pine, 6 percent; western larch (*Larix occidentalis*), 12.5 percent; and white fir, 8 percent (Jarvis 1963). It is thus evident that at rates bark would be applied, large amounts of tannins are introduced into the soil. Despite this, no toxic effects have been reported nor do they appear likely in view of the rapid decomposition of cork previously mentioned. However, tannins combine with proteins and reduce the rate of protein decomposition, as estimated from the production of carbon dioxide in liquid media inoculated with soil (Basaraba and Starkey 1966). Tannins alone decomposed more slowly than tannin-protein complexes, but even at 2-percent concentration, tannins were 12 percent decomposed in 18 days at pH 4 and 24 percent at pH 7. The inhibitory effect of tannins on plant residue decomposition is attributed to inactivation by tannin of microbial exoenzymes (Benoit and Starkey 1968).

Recent studies in our laboratory have shown that in each of two widely different soils, additions of purified tannin (tannin, 97 percent; sugars, 0.1 percent; ash, 2.07 percent; carbon, 55.69 percent; nitrogen, 0.12 percent) equivalent to 2,000 p.p.m. carbon were 22 percent decomposed in 180 days, as indicated by CO_2 evolution. At the same

time, the mold and bacterial populations were approximately doubled.

Western redcedar bark may be toxic to plants, although it is presently being used extensively for mulching in the Eugene, Oregon, area with no untoward results so far reported. Lunt and Clark (1959) found incense-cedar bark in a 50-50 soil mix to be slightly toxic. Allison (1965) found both bark and wood of incense-cedar to be toxic to garden peas. Wood of cedar, and to some extent that of redwood and western juniper (*Juniperus occidentalis*), contains thujaplicins and polyphenols which retard decay. Thujaplicins are water soluble and can be toxic to young roots on direct contact (Krueger 1968). Before use of such woods on plants, leaching of the material by copious irrigation is advisable.

Table 7. — Effect of -10+40 mesh Douglas-fir bark on nitrogen transformation in Woodburn silt loam soil

Treatment	N	Ammonification at 5 days	Nitrification at 30 days
	P.p.m.	*Percent*	*Percent*
Soil only	1,050	1	1
Soil plus additives:			
Peptone (15.8 percent N)	1,000	69	7
Bark (0.14 percent N) at 100 tons per acre	140	0	0
Bark plus peptone	1,140	58	6
Ammoniated bark (1.39 percent N) at 100 tons per acre	1,390	44	4

Table 8. — Effect of -10+40 mesh Douglas-fir bark and other additives on nitrification of $(NH_4)_2SO_4$ in Woodburn silt loam soil

Treatment	N	Nitrification at 30 days
	P.p.m.	*Percent*
Soil only	1,050	2
Soil plus additives:		
$(NH_4)_2SO_4$	200	20
$(NH_4)_2SO_4$ $+CaCO_3$ at four tons per acre	200	43
Bark (0.14 percent N) at 50 tons per acre	70	0
Bark + $(NH_4)_2SO_4$	270	2
Ammoniated bark (1.39 percent N)	200	5
Ammoniated bark (1.39 percent N) at 50 tons per acre	700	2

Agricultural uses of bark

Mulching

A mulch is any material placed on the soil surface primarily to prevent evaporative water loss or to suppress weed growth. Mulches also minimize temperature fluctuations in the plant root zone and prevent wind and water erosion of soil. Mulches have esthetic value, encourage earthworm populations, and improve the root environment for many plants.

Many different materials can be used for mulching: dust, stones, paper, plastic sheeting, asphalt emulsions, bark, sawdust, straw, and other crop residues. An ideal mulching material should be safe for plants and animals, pleasant and easy to apply, attractive, long lasting, noninjurious to soil microflora, and an eventual source of soil humus. An excellent review of mulches, their properties, effects, and selection for landscaping has been presented by Roberts (1968).

Bark is an excellent mulching material. It is superior to sawdust because it has a more pleasing color and texture and reflects less heat from its surface to the undersides of plants. It is also better than straw because it is more pleasing in appearance, longer lasting, less a fire hazard, and does not rapidly lose volume. Moreover, unlike most crop residues used for mulching, bark is free of weed seeds.

Size and distribution of ground bark particles is important to mulching use. There should be no excess of fines, which cause disagreeable dust in handling and may also cause compaction sufficient to retard aeration and infiltration of water. The ideal product is difficult to define, but a screened grind, ranging from one-half inch to fines with the majority of particles ranging from one-fiftieth to one-eighth inch (approximately 32 to 6 mesh), may be generally satisfactory. Particle-size distribution of two samples of milled bark and sawdust from different sources is shown in table 9. The mill-run sawdust sample has a desirable minimum of fines with fewer of the smaller fines.

Some bark, notably that of western redcedar and coast redwood, yields small particles that are long and fibrous. Hemlock bark contains a desirable assortment of particles, including those that are short and fibrous. Milled bark sometimes includes appreciable amounts of wood removed by cutter-head debarkers. Too much wood detracts from the appearance. Hemlock and white fir bark are more pleasant to handle than that of Douglas-fir, which has sharp, stiff bast fibers about 1 millimeter long. These can be quite irritating to the skin and in aggravated cases may even induce infection. However, they are not noticeable in ammoniated or composted bark, and pelletizing renders them innocuous.

Bark, as well as other organic mulches, eventually may incorporate with the soil and decompose, adding to the humus supply and improving the soil physically by increasing aggregation. Bark decomposition by microbes requires available nitrogen which, in wood residues, is nearly always very low (tables 2 and 3). If microbes attacking sawdust and bark do not find sufficient nitrogen therein, they absorb their requirement from the soil, thus competing with plant roots. Plant growth reduction as a result of this competition may be avoided by addition of nitrogen fertilizer to adjust the ratio of carbon:nitrogen to near 25:1.

The nitrogen addition (table 10) need not, however, be based on the total carbon content of the material because only part of the substance, 5 to 10 percent in the case of bark, is water soluble (table 11) and thus more readily available to attack by microbes than are the resistant lignocelluloses. In practice, it usually suffices to add 5 to 10 pounds of fer-

Table 9. — Particle-size distribution of bark and sawdust mulch samples

Mulch sample	Mesh designation, Tyler standard sieves									
	5	10	20	40	60	80	100	150	200	>200
	Percent retained on screen									
Bark:										
Douglas-fir (hammermilled)	2.6	20.3	20.0	17.7	15.7	8.0	4.2	4.0	3.6	4.3
Douglas-fir (hogged)	39.8[1]	29.4	9.5	13.1	2.9	1.7	.8	1.1	1.0	.2
Sawdust:										
Douglas-fir (mill run)	17.7	18.6	33.2	18.1	5.6	2.6	1.8	1.8	.7	.6
Douglas-fir (gangsaw)	0	29.3	40.9	23.3	3.3	1.3	.6	.5	.5	.2
Western hemlock (gangsaw)	0	30.3	41.7	20.9	3.6	1.3	.5	.5	.4	.3

[1] *>1/2 inch, 1.4 percent; <1/2 inch but >1/4 inch, 38.4 percent.*

Table 10. — Nitrogen fertilizer requirements for optimum decomposition of crop residues

Crop residue	Nitrogen content	Nitrogen required to raise N to 2-percent concentration
	Percent	*Pounds per ton*
Alfalfa	2.40	0
Green vetch	4.50	0
Barley hay	1.20	16
Corn stalks	.90	22
Barley stubble	.60	28
Western hemlock bark	.27	35[1]
Douglas-fir bark	.12	38[1]

[1] *Major constituents are resistant to decomposition. Thus, only 5 pounds per ton is required to satisfy N demand of water-soluble materials.*

tilizer nitrogen to each ton, dry basis, of mulch at the time of application. About 2½ to 5 pounds of nitrogen per ton should be added the second year to care for the more slowly decomposable constituents. After this, no further nitrogen additions should be required; the nitrogen previously assimilated by microbes will be released following their death and will become available for succeeding generations. Such repartition and reassimilation will not occur unless plant demands and leaching losses are compensated.

The foregoing rule for applying supplemental nitrogen to an organic mulch can be safely applied only in the case of moderately thick mulches. A 1-inch bark mulch weighs approximately 20 tons per acre, ovendry basis. At the suggested rate of fertilizer application, 500 to 1,000 pounds per acre of ammonium sulfate (21 percent N), or the same nitrogen equivalent of another form of fertilizer, would be required. Adequate irrigation after heavy applications of nitrogen fertilizer will avoid salt injury to plants.

Deep mulches of bark or sawdust, with appropriate fertilizer additions, are considered almost essential in the successful culture of blueberries and certain ornamentals such as azaleas and rhododendrons on mineral soils in Oregon. Thick mulches which, for crops such as blueberries, may be maintained at a depth of 4 to 6 inches when fully settled, require addition of fertilizer in increments judiciously timed with irrigation needs. In actual mulching practice, additional bark or sawdust is applied every other year at a rate of about 1 inch to compensate for settling and decomposition (Roberts and Mellenthin 1959). Relatively little of the thick mulch is in contact with the soil at any time, so little additional fertilizer nitrogen is required in any one year until plant roots extend into the mulch.

Nitrogen added to an organic mulch must be regarded only as food for the microbes decomposing the mulch; nitrogen required for plant nutrition is an additional demand. To a lesser extent, soil microbes also demand available phosphorus and sulfur. In some soils, these nutrients may be limiting to microbial and plant growth and should be supplied by appropriate fertilizing.

Organic mulches decompose mainly at the zone of contact between the underside of the mulch and the mineral soil surface. Mulching

Table 11. — Analysis of cold-water solubles in bark, wood, and moss peat

Species	pH		Water soluble[1]		Kjeldahl nitrogen		C/N ratio	
	Bark	Wood	Bark	Wood	Bark	Wood	Bark	Wood
			Percent					
Western redcedar:								
Untreated	3.2	3.5	2.95	6.99	0.14	0.06	378:1	810
Extracted	4.5	4.6	--	--	.13	.06	392:1	835
Redwood:								
Untreated	3.2	4.4	2.35	1.67	.11	.07	473:1	753
Extracted	4.8	5.6	--	--	.11	.06	457:1	876
Red alder:								
Untreated	4.6	5.8	11.64	1.43	.72	.13	71:1	377
Extracted	5.0	6.0	--	--	.81	.15	62:1	320
Western hemlock:								
Untreated	4.1	6.0	3.95	3.47	.27	.04	212:1	1,234
Extracted	4.4	4.4	--	--	.24	.03	223:1	1,618
Ponderosa pine:								
Untreated	3.8	4.4	4.35	2.68	.12	.04	422:1	1,297
Extracted	3.9	4.2	--	--	.13	.06	429:1	895
Sitka spruce:								
Untreated	4.9	4.1	10.89	1.27	.41	.04	130:1	1,214
Extracted	6.4	6.4	--	--	.40	.04	127:1	1,194
Douglas-fir:								
Untreated	3.6	3.4	5.49	4.65	.12	.04	471:1	1,268
Extracted	3.8	3.3	--	--	.11	.04	513:1	1,242
Sour sawdust	--	2.0	--	12.81	--	.06	--	893
Moss peat:								
Untreated	3.8		1.04		.83		58	
Extracted	4.4		--		--		--	

[1] *Total solids in 12 successive 1:10 water extractions, 24 hours each.*

materials low in nitrogen may reduce available nitrogen in this contact zone and thus encourage nonsymbiotic nitrogen fixation by *Azotobacter* and certain species of *Clostridium.* In this way, some of the nitrogen deficiency may be relieved.

Other properties of mulching materials requiring some consideration are bulk density, heat capacity, and reflectance. Bulk density varies with particle size and distribution; fines increase the density. Agricultural grades of ground bark are heavier than moss peat but lighter than sawdust. Ground bark, which typically includes large particles minimizing the tendency to pack, is favorable to infiltration of water.

The heat capacity of an organic mulch depends largely upon its water content. Bark can hold water in amounts several times its weight, in some cases even more than wood of comparable particle size (table 12). Air-dry bark is also difficult to wet (table 13), depending on particle-size distribution and tree species from which the bark came.

The color of a mulching material is important. Sawdust, generally light colored and smooth textured, reflects heat which may cause sun scald of low leaves and fruit. Bark is darker than sawdust so it absorbs light and heat more readily and also loses moisture more rapidly because of evaporation induced by absorbed heat.

Mulches importantly affect soil microclimate (Roberts 1968) through their insulating properties. In the presence of a mulch, the rate of heat exchange is reduced as is also total heat conducted to the soil surface during the day and that released from the soil to the atmosphere at night. A mulched soil surface provides a cool root medium for plants growing in exposed locations during hot weather. However, use of a mulch can expose plants to so-called radiation frost in fall and spring when heat loss from soil to atmosphere may be a critical requirement for plants that have not developed adequate cold resistance.

For meaningful calculations, in determination of the fertilizer requirements for an application of bark volume weight data on the ovendry (105° C.) basis are essential, but no precise information is to be found in the literature. Various papers, trade brochures, and letters [18] give weights ranging from 9.7 to 30.6 pounds per cubic foot for ovendry Douglas-fir bark. These differences must be due to variations in particle size and compaction. A weight of 3,000 pounds per unit, or 25 pounds per cubic foot, has been mentioned for hogged bark, species and water content not indicated. For bagged bark, 18 pounds per cubic foot has been suggested.

Thin mulches are useful where soil crusting prevails. Tests with Loamite,[19] placed over planted seeds of broccoli, lettuce, celery, aster, and other plants, have shown plant emergence increases 40 to 80 percent over unmulched seedbeds. Higher emergence rates permit planting fewer seeds, thus reducing thinning labor (Ellis 1965). Seedlings in treated areas also emerge earlier in the season. Seedlings in treated areas also emerge earlier in the season. Bark of approximately −10 mesh size may also favor seedling emergence. Light dressings of bark are also extensively used on newly seeded lawns.

Thick mulches of bark are excellent for blueberries, raspberries, and orchards, and give better results than straw (Latimer 1956, Roberts 1968). An initial bark application 8 to 10 inches thick, as sometimes applied on orchard soils, should last about 10 years. The advantages would be in weed control, moisture retention, elimination of cultivation, and year-around use of orchard equipment. The mulch also frees the top soil moisture and nutrients for tree use and prevents root damage that often results from cultivating bare soil.

Soil Conditioning

Incorporating bark or other organic matter physically benefits soil. Fine-textured or heavy soils are rendered more porous, which may improve aeration and drainage. This action results not only from soil dilution — the mechanical intermixing of bark particles with soil — but also from subsequent decom-

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[18] *Summary of information concerning weight and volume of bark. R. A. Currier. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Mimeogr., 3 pp., [n. d.] Privately distributed.*

[19] *A soil amendment-fertilizer manufactured from sawdust by the Fersolin Corp., associate of Pope & Talbot, Inc., San Francisco, Calif. (Farber and Hind 1959) (fig. 3).*

Table 12. — Water-holding capacity of bark, wood, and moss peat, by species and mesh[1] size

Species	Bark		Wood	
	−10+40	−40	−10+40	−40
	Percent ovendry weight			
Douglas-fir[2]	283	340	330	440
Hemlock	307	368	273	614
Ponderosa pine	324	566	243	665
Sitka spruce	159	215	616	998
Redcedar	584	490	393	658
Coast redwood	500	400	320	356
Red alder	277	270	418	627
Moss peat	765	450	--	--

[1]*See text footnote 12.*

[2]*A 25-millimeter cube of bark had a water-holding capacity of 60 percent; a −5 mesh sample of wood had a capacity of 228 percent.*

Table 13. — Relative wettability of bark and wood of various species and mesh[1] sizes while being stirred in water[2]

Species	Bark		Wood	
	−10+40	−40	−10+40	−40
Red alder	3	2	3	2
Douglas-fir	2[3]	1	3	3
Hemlock	3	2	3	3
Ponderosa pine	3[3]	3	3	3
Sitka spruce	3	3	4	4
Redcedar	2	2	3	3
Coast redwood	2	2	3	3
Moss peat	3	2	--	--

[1]*See text footnote 12.*

[2]*1, very slowly; 2, slowly; 3, rapidly; 4, very rapidly.*

[3]*Except cork.*

Table 14. — Cation exchange capacity (CEC) of some organic residues and soils

Material	Mesh size[1]	CEC
		Meq./100 g.
Douglas-fir:		
Bark	+5	44.8
Bark	–10+40	39.7
Bark	–40	60.5
Wood	–10+40	39.5
Wood	–40+100	28.2
Wood	–100+200	15.0
Red alder:		
Bark	–10+40	40.4
Wood	–10+40	59.0
Wood	–100+200	7.5
Ponderosa pine wood	–10+40	13.5
Humin[2]		38.8
Wheat straw	–10	39.4
Wheat straw	–60	19.4
Moss peat	–10	120.6
Delhi loamy sand	–10	2.7
Walla Walla silt loam	–10	18.6
Chehalis silty clay loam	–10	24.3

[1] *See text footnote 12.*

[2] *Residue from treatment of wood waste with hydrochloric acid in the manufacture of levulinic acid by Crown Zellerbach Corp.*

position products and humus formation, which increase aggregation or granulation and thus improve tilth. Organic matter additions to coarse-textured soils increase their capacity to hold water in a form available to plants. Amount of organic additions to soil, however, must be controlled. Excessive additions may increase aeration so much that during hot weather the soil will dry at an undesirably rapid rate. Under wet conditions, increasing the water-holding capacity of soil unduly may result in waterlogging and development of anaerobic conditions.

Cation exchange capacity (CEC) is appreciably increased. This is especially important in sandy soils and others low in humus. Ammonium, as well as other cations, is held against loss by leaching but is still available to plant roots and microbes. The CEC of ground bark may be two to three times greater than that of a silt loam soil (table 14). Phenolic acid polymers in bark have neutralization equivalents of about 100 to 200 milliequivalents to 100 grams. Uronic acid substances, in both wood and bark, have a CEC as high as 100.

Much that has already been said concerning mulches applies also to incorporation of bark with the soil. Adding supplemental nitrogen to organic matter is even more important with soil incorporations because the bark is mixed with the soil and offers close contact with plant roots. Microorganisms are more effective than plant roots in obtaining needed nitrogen. For this reason, the rate of supplemental nitrogen should be about twice that used for mulches; i.e., 10 to 20 pounds nitrogen per ton of bark to bring the C:N ratio to near 50:1.

As much as 100 tons per acre of bark may be used in soil conditioning. This amount corresponds to a layer 4 to 5 inches deep before mixing, or to a 10-percent addition, by weight, to a plow depth of 6-2/3 inches, equivalent to 2,000,000 pounds of mineral soil. Disking is preferred to plowing as a method of incorporation; it ensures better mixing and leaves some bark on the soil surface as protection against erosion.

Addition of organic matter to the soil surface, or in various degrees of incorporation, dilutes the soil. This immediate or gradual physical dilution can improve aeration of heavy soils and increase the water-holding capacity of light soils. Although mulches do not immediately dilute the soil, in wet climates or under irrigation deep mulches may hold enough excess water to impede aeration and create problems associated with denitrification, anaerobic respiration, and the development of certain root rot organisms (Roberts and Mellenthin 1959). These hazards are most likely to develop on heavy soils. Soil type, therefore, must be considered in the use of mulches.

In our laboratory, ovendry Douglas-fir bark in one piece 5 inches thick by 6 inches by 11 inches from an old-growth tree weighed 38.7 pounds per cubic foot. This compares with 34 pounds for air-dry (water content 12 percent) Douglas-fir lumber, or about 30 pounds per cubic foot, ovendry (Institute of Forest Products 1957). The actual weight of bark or sawdust mulch per acre-inch varies greatly according to water content, species, mechanical analysis, and degree of packing. For calculating field applications of ground bark, a value of 11 pounds per cubic foot or 20 tons per acre-inch is suggested to represent the ovendry weight. The actual weight of sawdust applied to soils is likewise difficult to determine from various published reports. A close approximation for mill-run Douglas-fir sawdust is 10 pounds per cubic foot or 18 tons per acre-inch, ovendry basis.

Weights of 1 cubic foot of several brands of bagged bark purchased on the local market and for sawdust from a pile used for mulching are shown in table 15.

All the bark contained wood particles, mostly slivers, the larger of which to some extent detracted from its appearance. Although it is not economically feasible to avoid all wood slivers, etc., they should be kept to a minimum by appropriate screening. Note in table 15 that the Douglas-fir bark had lowest percentage of +5 and -5+10 fractions and contained the lowest percentage of wood.

Soil Mixes

Soil mixes containing relatively large fractions of organic matter and inorganic amend-

Table 15. — Water content, weight, and particle-size distribution of commercially prepared ground bark and sawdust

Property	Douglas-fir bark	Douglas-fir and hemlock bark, mixed	Hemlock bark	Douglas-fir sawdust, mill run
Water (percent)	66.7	88.8	80.2	73.9
Weight per cubic foot (pounds):				
Wet	17.8	20.7	20.1	16.9
Ovendry (105° C.)	10.7	11.0	11.2	9.7
Mechanical analysis[1] (percent of total):				
+5 mesh	4.4	26.1	20.0	6.3
−5+10 mesh	12.0	22.0	24.4	24.6
−10+40 mesh	36.6	32.8	36.0	62.1
−40 mesh	47.0	19.1	19.6	7.0
Wood particles (percent of total):				
+5 mesh[2]	1	2	2	20
−5+10 mesh[3]	10	5	5	10
−10+40 mesh[4]	1	5	10	5
Percent of total sample	2	3	5	7
−40 not determinable				

[1] *Determined on 200-gram ovendry samples after a mechanical shaking through Tyler standard sieves for 10 minutes.*

[2] *Mostly slivers about 1 to 2 inches long.*

[3] *Estimated – mostly slivers about 1 inch long.*

[4] *Estimated – mostly slivers about 1/2 to 3/4 inch long.*

ments are widely used for growing potted plants in nurseries and for special purposes in ornamental horticulture. Additions of organic matter such as moss peat, sawdust, and bark increase porosity, aeration, and water retention and decrease bulk density. Physical properties of these organic components and their influence on soil aeration and water relationships are most important (table 16). Low bulk density is desirable because it reduces handling effort and transportation cost of potted plants. Water conduction and retention properties are important to irrigation and control of salinity.

Water conduction and retention is determined by particle-size distribution and physical character of components and their combinations in the mix. A high water-holding capacity does not necessarily assure more available water; much of the water held requires more work or suction than the plant roots can exert (fig. 12, table 17) (Baver 1959, Feustel and Byers 1936, Lyon et al. 1950, Richards et al. 1964, Taylor 1965). Capillary water is optimum until at about 15 atmospheres tension the roots begin to have difficulty in absorbing water; wilting may

Table 16. — Physical properties of soil-mix components and some mixtures[1]

Soil components	Bulk density		Porosity	Moisture retention		Air space after drainage
	Dry	Wet				
	Pounds per cubic yard		*Volume percent*	*Volume percent*	*Weight percent*	*Volume percent*
Clay	1,585	2,505	59.6	--	59	4.7
Fine sand	2,400	3,050	44.6	--	27	5.9
Perlite, 3/16 to 1/4 inch	150	470	75.3	--	213	56.3
Vermiculite, 3/16 inch	182	1,077	80.5	--	492	27.5
Sphagnum peat	163	1,228	84.2	--	560	25.4
Redwood sawdust	296	1,126	77.2	--	280	27.9
Redwood bark, 3/8-inch mesh	210	725	80.3	--	245	49.5
Manure, dairy	580	1,630	74.3	--	182	7.6
Clay and fine sand	2,203	2,898	47.4	41.5	32	6.9
Clay and sphagnum peat	910	1,930	71.0	61.0	112	10.0
Fine sand and sphagnum peat	1,540	2,330	57.5	47.0	51	10.5
Fine sand and redwood sawdust	1,490	2,280	58.7	47.0	53	11.7
Fine sand and redwood bark	1,570	2,300	56.8	43.5	46	13.3

[1] *O. A. Matkin. Unpublished data. 1962.*

occur near 30 atmospheres. If the water is saline, osmotic tensions impose additional stress upon the plant. Adding organic materials and soil conditioners to soil generally decreases available water but increases infiltration and aeration. Only in coarse-textured soils do organic additions consistently increase available water. This is in contrast to humus or native soil organic matter, which is highly decomposed, stabilized, and intimately associated with soil particles, improving structure and providing more porosity favorable for holding available water.[20] It should be emphasized that the performance of an additive cannot be predicted solely on the basis of its inherent properties; the mixture must also be considered.

Richards et al. (1964) found that 30-percent additions of redwood and pine shav-

[20] *The sorptive capacity of bark has recently been used in Sweden to remove oil slicks from water surfaces. Pine bark powder spread on the water's surface absorbs the oil and forms clumps which can be collected and burned (Anonymous 1967). The technique has been refined to utilize sausage-shaped booms stuffed with bark; after the oil is absorbed, the booms can be used as fuel (Geraghty 1968). Silicone-coated sawdust also is useful in combating oil slicks. After absorbing oil, the sawdust sinks and the oil is subsequently decomposed by hydrocarbon bacteria.*

Table 17. — Relation of organic matter to water-holding capacity and availability of soil water[1]

(In percent)

Soil, sand, peat, and their mixtures	Water-holding capacity	Moisture equivalent	Wilting	Available water	
				Percent	Percent of water-holding capacity
Clay loam soil	44.3	20.2	7.1	13.1	30
Quartz sand	28.3	1.4	.57	.83	29
Moss peat	1,057.0	166.0	82.3	83.7	8
Reed peat	289.0	110.0	70.7	39.3	14
Half clay soil and half moss peat	114.0	31.0	14.5	16.5	14
Four-fifths clay soil and one-fifth moss peat	57.4	21.6	8.5	13.1	23
Half quartz sand and half moss peat	89.1	12.7	5.2	7.5	8
Four-fifths quartz sand and one-fifth moss peat	47.8	5.6	1.8	3.8	8

[1] *From Feustel and Byers (1936).*

Table 18. — Lime requirement and pH of soil, bark, and mixtures, before and after autoclaving[1]

Soil and mixture	pH[2]		Lime requirement[3]	
	Before	After	Before	After
			Pounds per ton	
Chehalis sandy loam	5.2	5.6	0.1	1.2
Douglas-fir bark	3.6	3.5	24	31
Douglas-fir sawdust	3.5	3.3	17	19
Soil plus 10 percent of bark	4.8	4.9	4	25
Soil plus 10 percent of sawdust	5.0	5.0	6	11

[1] *2 hours at 15 pounds p.s.i. (gage pressure).*

[2] *pH of soil determined on 1:5 water suspensions; pH of bark and sawdust determined on 1:20 water suspensions.*

[3] *$CaCO_3$ required to raise pH to 7.0.*

CLASSIFICATION OF SOIL – WATER–PLANT RELATIONSHIP

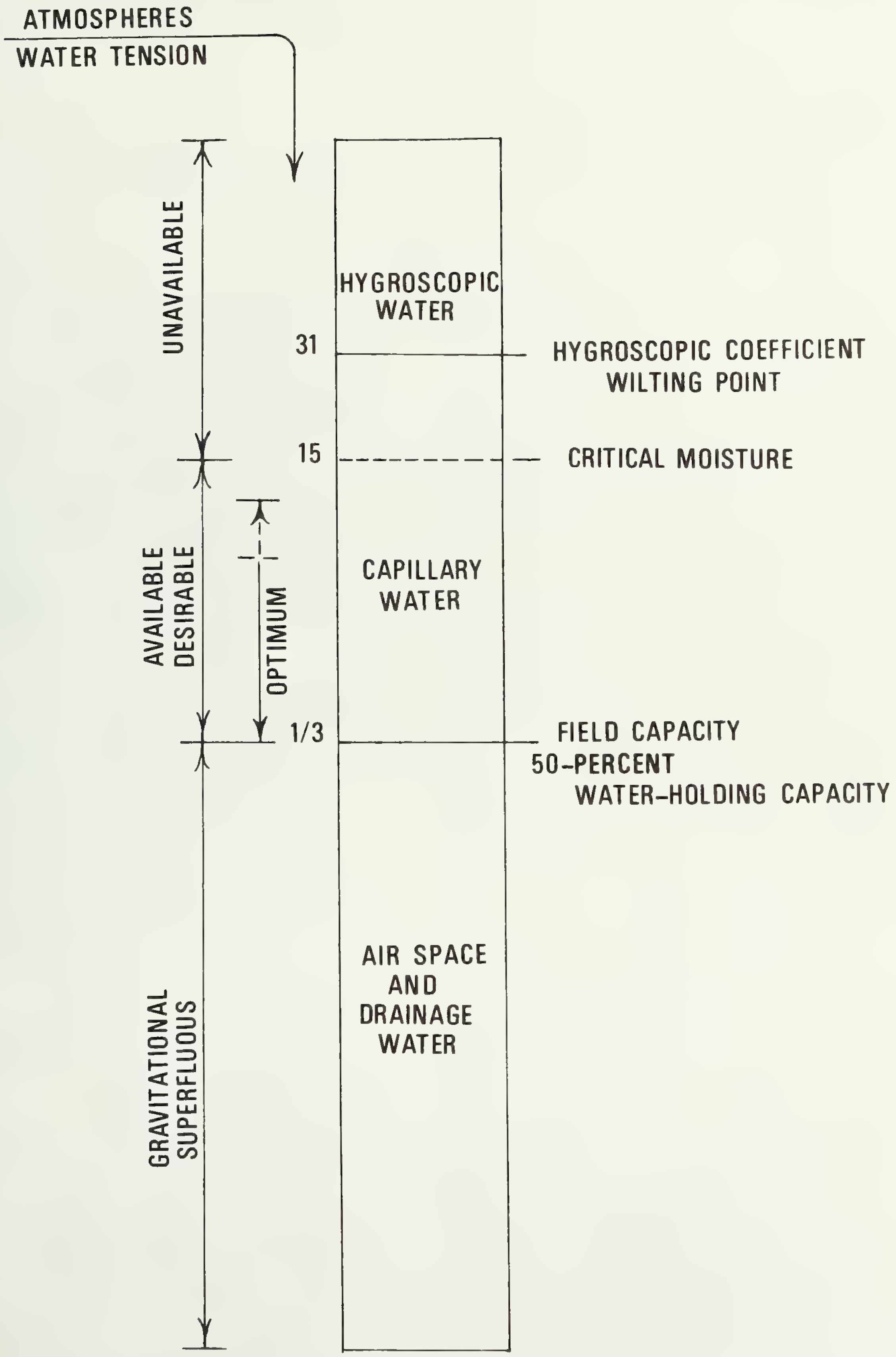

Figure 12. — Classification of soil-water-plant relationships.

ings in soil mixes increased water conductivity about five times; 60-percent additions gave increases near 20 times. Moss peat was much less effective. Water, released to plant roots by the mixture at low tensions up to 30 centibars (cb), approximately 4 atmospheres, was only slightly increased by the 30-percent additions; 60-percent additions about doubled the amount of water released. The amendments had little effect on release of water between 30 and 50 cb. Because of the limited amounts of water released above 30 cb, an irrigation program safe for potted plants should be based on irrigation when tensiometer readings reach 30 cb.

Fir, hemlock, pine, and redwood barks are often used in soil mixes in proportions as high as 50 percent (Baker 1957, McNeilan 1967). These artificial mixtures are used because they (1) permit standardization of physical, chemical, and biological properties of the media; (2) facilitate addition of formulated nutrients on schedule; and (3) are readily sterilized. Changes in pH and lime requirement due to sterilization by autoclaving may be important (Matkin et al. 1957). However, only small differences resulted when a sandy loam soil plus 10 percent Douglas-fir bark or sawdust was autoclaved (table 18).

Milled bark from loblolly and shortleaf pine, alone or mixed 50-50 with sand or perlite, is an excellent rooting medium for ornamental plants (Pokorny and Perkins 1967). Cuttings of some species rooted best in 100-percent bark (Pokorny and Gugino 1967). The bark also showed promise as an amendment for potting media and for container plants (Pokorny 1966).

Rooting of newly planted balled shrubs or trees can be benefited by backfilling the planting hole with a mixture of bark or other resistant organic matter and soil. Nitrogen fertilizer must be added as necessary. Loamite has been used in this way with much success in planting balled avocado and citrus trees (Anonymous 1963). The amended backfill is less likely to crack and settle and thus possibly break tender roots that venture from the ball. Aeration and water movement may also be improved.

Bark could replace sphagnum moss now used as a wrapping around tree seedlings planted on rocky sites (Hammer and Broerman 1967). With added fertilizer, an initial nutrient supply would be provided and, during dry periods, a reserve of moisture. The packaging may also give protection against possible adverse effects of herbicides used on the surrounding soil (Bickford and Hermann 1967). A 1:1 mixture of topsoil and moss peat appears advantageous for aiding survival of Douglas-fir seedlings on dry sites (Bickford and Hermann 1967).

Facilitating Drainage of Agricultural Land

Hundreds of thousands of acres of agricultural land require supplemental drainage to assure best crop growth. In this regard, a potential use exists for large tonnages of Douglas-fir bark as trench filler or backfill to overlay or substitute for tile in drainage ditches. Research on this use for bark is in progress in the Willamette Valley of Oregon.

Douglas-fir bark is especially suited for backfill purposes because fairly large, broken chunks free of fines are required to prevent drain clogging. When in place and covered with about 1 foot of soil, the bark would be more or less saturated with water most of the time. Under consequent anaerobic conditions, large pieces of bark would remain essentially undecomposed and should remain in place for many years.

Base Material for Composting Food Processing Wastes

Tremendous quantities of food processing wastes are now treated in stabilization ponds or sewage plants for disposal. Waste from poultry processing plants and canneries could be used for composting with bark, yielding a useful product and at the same time alleviating disposal and pollution problems. Suggestions for such use have been offered by Ivory and Field (1959).

Animal and Poultry Bedding

Bark is used increasingly as bedding in animal stalls, poultry houses, and stockyards because of the growing shortage of shavings and sawdust. After such use, the bark, now mixed and impregnated with manure, has premium value as a soil amendment and fertilizer.

Other uses of bark

Backfill for Septic Tank Drains

Another potentially large use for bark chunks is in preparation of septic tank drainfields. The method of use and drainage action is the same as described for agricultural land drainage.

Filter Bed Material for Effluent Disposal

Bark can be used as a substitute for stone or gravel in trickling filter beds for sewage and cannery effluent disposal. After use, the bark should be piled and allowed to stand until the slime decomposes. The product would be enriched with nitrogen and other nutrients derived from the sewage and also would be largely free of bark dust (Burton 1959).

Road and Highway Slope Stabilization

Bark has a potentially important use as a soil stabilizer for highway banks and other slopes. Economic application could be made with suitably designed hydraulic spreading equipment, such as is now widely used for applying straw and other organic materials to steep cutbanks and fills.

Ameliorating Forest Soil Properties After Timber Harvest

Main goals in good management of forest soils and watersheds include maintaining a protective organic cover on the soil surface, incorporating the maximum possible amount of organic matter with the soil, and providing maximum soil fertility. Bark, now removed from the forest on the log and transported to the mill to become a disposal problem, could be left at the logging site to contribute substantially to achieving the foregoing goals of good land management.

Portable machinery is now available[21] to remove bark and limbs from standing trees slated for harvest. Such machines are now used in Finland.[22] Benefits to be realized from the practice of leaving bark scattered over a logged area include not only those previously mentioned but also lowered log transportation costs and alleviation of air and water pollution associated with present methods of bark disposal.

Improving Water Quality in Municipal Watersheds

In certain soils, including some forested areas, nitrates accumulate during warm weather when moisture is favorable. Later, under heavy rainfall, the nitrates are leached into streams supplying water for domestic use, sometimes raising the nitrate concentration sufficiently to become a hazard to public health (Bormann et al. 1968). More than 10 p.p.m. nitrate nitrogen may induce methemoglobinemia in infants and is considered generally dangerous to human health (Lenain 1967).

By irrigating stands of oak and red pine with waste water from a sewage treatment plant, Pennypacker et al. (1967) found that quality of the effluent was much improved by removal of much of the phosphorus and ABS (alkylbenzenesulfonate, a hard detergent, resistant to biodegradation). Nitrates, although removed to a large extent in the underlying soil, increased twofold to threefold in the forest floor. It would seem that such nitrate buildup could be avoided by addition of bark to a watershed soil; microbes, attacking such an organic addition of wide C:N ratio, would assimilate the nitrate and thus prevent its leaching into water supplies.

Miscellaneous

Filler for commercial fertilizers.

Carrier or diluent for pesticides.

Eliminator of mud problems in barnyard and feedlots.

Ameliorator of salt conditions on alkali spots. A mulch would minimize buildup of salts on the soil surface.

[21] *Personal communication from H. P. Schneider, Forest Service Products, Inc., Wheaton, Ill.*

[22] *Personal communication from Dr. T. Norris, Sweden Forest Products Research Laboratory, Stockholm O. Sweden. 1968.*

Literature cited

Anonymous.
[n. d.] Fir and pine bark as a soil amendment. Tech. Bull., 20 pp., illus. Scott Lumber Co., Burney, Calif.

____
1963. Loamite soil amendment use in planting balled avocados and citrus. Res. Dep., Pope & Talbot, Inc., Loamite Div., San Francisco, Calif. 2 pp.

____
1967. Swedes use bark to combat oil slicks. Air & Water News 1(41), unnumbered pages. New York: McGraw-Hill.

Allison, Franklin E.
1965. Decomposition of wood and bark sawdusts in soil, nitrogen requirements, and effects on plants. U. S. Dep. Agr. Tech. Bull. 1332, 58 pp., illus.

Baker, K. F. [ed.]
1957. The University of California system for producing healthy container-grown plants through the use of clean soil, clean stock, and sanitation. Calif. Agr. Exp. Sta. Manual 23, 332 pp.

Basaraba, Joseph, and Starkey, Robert L.
1966. Effect of plant tannins on decomposition of organic substances. Soil Sci. 101: 17-23, illus.

Baver, L. D.
1956. Soil physics. Ed. 3, 489 pp., illus. New York: Wiley & Sons.

Benoit, Robert E., and Starkey, Robert L.
1968. Enzyme inactivation as a factor in the inhibition of decomposition of organic matter by tannins. Soil Sci. 105: 203-208, illus.

Bickford, M., and Hermann, R. K.
1967. Herbicide aids survival of Douglas-fir seedlings planted on dry sites in Oregon; root wrapping has little effect. Tree Planters' Notes 18(4): 5-8, illus.

Bollen, W. B., and Glennie, D. W.
1961. Sawdust, bark and other wood wastes for soil conditioning and mulching. Forest Prod. J. 11: 38-46, illus.

__________ and Lu, K. C.
1957. Effect of Douglas-fir sawdust mulches and incorporations on soil microbial activities and plant growth. Soil Sci. Soc. Amer. Proc. 21: 35-41, illus.

__________ and Lu, K. C.
1966. "Sour" sawdust mulch may damage ornamentals. Oreg. State Univ. Ornamental & Nursery Dig. 10(1): 2, illus.

Bollen, Walter B., and Glennie, D. W.
1963. Fortified bark for mulching and soil conditioning. Forest Prod. J. 13: 209-215, illus.

Bollen, Walter Beno.
1959. Microorganisms and soil fertility. Oreg. State Agr. Coll. Monogr. 1, 25 pp., illus. Corvallis: College Press.

Bollerslev, Karl.
1968. Bark processing problems. Forest Prod. J. 18(6): 19-20, illus.

Bormann, F. H., Likens, G. E., Fisher, D. W., and Pierce, R. S.
1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. Science 159: 882-884, illus.

Bremner, J. M., and Shaw, K.
1957. The mineralization of some nitrogenous materials in soil. J. Sci. Food Agr. 8: 341-347, illus.

Burton, R. Ed.
1959. Making fertilizer — soil conditioner from bark as a trickling-filter media. Forest Prod. J. 9(4): 19A-22A, illus.

Cadman, C. H.
1960. Inhibition of plant virus infections by tannins. *In* Phenolics in plants in health & disease, J. B. Pridham (ed.). Plant Phenolics Group Symp. Proc., Bristol, 1959, pp. 101-105, illus. New York: Pergamon Press.

Cook, M. T.
1911. The relation of parasitic fungi to the contents of the cells of the host plant. I. The toxicity of tannins. Del. Agr. Exp. Sta. Bull. 91, 77 pp., illus.

Creech, J. L., Dowdle, R. F., and Hawley, W. O.
1955. Sphagnum moss for plant propagation. U. S. Dep. Agr. Farmer's Bull. 2085, 10 pp., illus.

Cruickshank, E. D.
1968. Upper Willamette Resource Conservation and Development Project Area, a directory of bark producers and facilities in Benton, Lane and Linn Counties. Oreg. State Forest. Dep., Corvallis, 15 pp., illus.

Dachnowski-Stokes, A. P.
1931. Moss peat, its uses and distribution in the United States. U. S. Dep. Agr. Circ. 167, 11 pp., illus.

Dost, W. A.
1965. Agricultural and horticultural use of wood residues in California. Forest Prod. J. 15: 450-452, illus.

Dunn, S.
1956. The influence of waste bark on plant growth. N. H. Agr. Exp. Sta. Bull. 435, 19 pp., illus.

Ellis, D. S.
1965. Use of Loamite soil amendment to improve emergence and early growth of commercial vegetable and flower seed plantings. Res. Dep., Pope & Talbot, Inc., Loamite Div., San Francisco, Calif., 10 pp., illus.

Ellis, E. L.
1959. The effects of environment and decay on mineral components of grand fir wood. Marine Boring and Fouling Organisms. Friday Harbor Symp., pp. 477-512, illus. Seattle: Univ. Wash. Press.

____
1965. Inorganic elements in wood. *In* Cellular ultrastructure of woody plants, pp. 181-189. Syracuse, N. Y.: Syracuse Univ. Press.

Farber, E., and Hind, R. R.
1959. Process for converting sawdust into fertilizer. Forest Prod. J. 9: 340-344, illus.

Feustel, I. C., and Byers, H. G.
1936. The comparative moisture-absorbing and moisture-retaining capacities of peat and soil mixtures. U. S. Dep. Agr. Tech. Bull. 532, 26 pp., illus.

Gardner, Wright A.
1926. The decomposition of toxins by soil organisms. Ala. Polytech. Inst. Agr. Exp. Sta. Bull. 225, 38 pp.

Geraghty, James J. [ed.]
1968. Pine bark said to check oil spill pollution. Water Newsletter 10(8): 3.

Gessel, Stanley P.
1959. Composts and mulches from wood waste. Inst. Forest Prod. New Wood-Use Ser. Circ. 33, 14 pp., illus. Seattle: Univ. Wash.

Gibbs, W. M., and Batchelor, H. W.
1927. Effect of tree products on bacteriological activities in soil: II. Study of forest soils. Soil Sci. 24: 351-363.

______________ and Werkman, C. H.
1922. Effect of tree products on bacteriological activities in soil: I. Ammonification and nitrification. Soil Sci. 13: 303-322, illus.

Gupta, Umesh C., and Reuszer, H. W.
1967. Effect of plant species on the amino acid content and nitrification of soil organic matter. Soil Sci. 104: 395-400.

Hammer, J. G., and Broerman, F. S.
1967. A comparison of three packaging methods for slash pine seedlings. Tree Planter's Notes 18(4): 3-4.

Henin, Y., Tagari, H., and Volcani, R.
1964. Effect of water extracts of carob pods, tannic acid, and their derivatives on the morphology and growth of microorganisms. Appl. Microbiol. 12: 204-209, illus.

Institute of Forest Products (State of Washington).
1957. Conversion factors for Pacific Northwest forest products. 28 pp. Seattle: Univ. Wash.

Ivory, E. P., and Field, P.
1959. Utilizing bark at a medium-size mill — processing and merchandising bark products. Forest Prod. J. 9(4): 28A-30A, illus.

Jarvis, J. C.
1963. Bark utilization study. Western Pine Ass. Res. Note 7.221, 12 pp.

Jung, Josef, and Hubbes, Martin.
1965. Growth inhibition of *Bacillus cereus in vitro* by glycosidal substances extracted from bark of *Fraxinus*. Can. J. Bot. 43: 469-474, illus.

Kennedy, Robert W.
1956. Fungicidal toxicity of certain extraneous components of Douglas-fir heartwood. Forest Prod. J. 6: 80-84, illus.

Koch, A., and Oelsner, A.
1916. Influence of pine resin and tannin on the nitrogen economy and physical properties of the soil. Centr. Bakt. Par. (II) 45: 107-118. (Abstr. in J. Chem. Soc. (London) 110: 454.)

Krueger, Kenneth W.
1968. Investigations of shingle tow packing material for conifer seedlings. Pacific Northwest Forest & Range Exp. Sta. U. S. D. A. Forest Serv. Res. Pap. PNW-63, 10 pp., illus.

Kurth, E. F.
1953. Chemicals from Douglas-fir bark. TAPPI 36(7): 119a-122a.

____
1958. Chemical analyses of mountain hemlock. TAPPI 41(12): 733-734.

______________ and Chan, Frank L.
1951. Dihydroquercetin as an antioxidant. J. Amer. Oil Chem. Soc. 28(10): 433-436, illus.

______________, Kiefer, Harry J., and Hubbard, James K.
1948. Utilization of Douglas-fir bark. Timberman 49(8): 130-131, illus.

Latimer, L. P.
1956. The comparative value of bark as a surface mulch for apples, blueberries, and raspberries. N. H. Agr. Exp. Sta. Bull. 435, Suppl., pp. 18-19.

Lenain, August F.
1967. The impact of nitrates on water use. J. Amer. Water Works Ass. 59(8): 1049-1054.

Lunt, O. R., and Clark, B.
1959. Horticultural applications for bark and wood fragments. Forest Prod. J. 9(4): 39a-42a.

Lutz, Harold John, and Chandler, R. F.
1946. Forest soils. 514 pp., illus. New York: Wiley & Sons.

Lyon, Thomas Lyttleton, Buckman, H. O., and Brady, Nyle C.
1952. The nature and properties of soils, a college text of edaphology. Ed. 5, 591 pp., illus. New York: Macmillan Co.

Macdonald, W. A., and Dunn, S.
1953. Sawdust composts in soil improvement. II. Pot culture studies with compost mixtures of sawdust and manure steam treated composts, and miscellaneous mixtures. Plant & Soil 4: 235-247.

McNeilan, R. A.
1967. Container mixtures and nutrition management for ornamental plants. Oreg. State Univ. Ext. Serv. Fact Sheet 126, 2 pp.

Mader, D. L.
1960 Effect of humus of different origin in moderating the toxicity of biocides. Ph.D. thesis, Univ. Wis., 63 pp. Emmaus, Pa.: Soil & Health Found.

Mater, J.
1967. Bark utilization: a review and projections. Forest Prod. J. 17(12): 15-20.

Matkin, O. A., Chandler, P. A., and Baker, K. F.
1957. Components and development of mixes. Sect. 6, pp. 86-107. *In* University of California system for producing healthy container-grown plants through the use of clean soil, clean stock, and sanitation, K. F. Baker (ed.). Calif. Agr. Exp. Sta. Manual 23, 332 pp.

Mattson, S.
1948. The constitution of the pedosphere. Ann. Agr. Coll. Sweden 5: 261-276, illus.

May, O. E., and Herrick, H. T.
1934. Some practical and theoretical aspects of mold metabolism. J. Bacteriol. 28: 145-151.

Neal, J. L., Jr., Bollen, W. B., and Lu, K. C.
1965. Influence of particle size on decomposition of red alder and Douglas-fir sawdust in soil. Nature 205: 991-993, illus.

Neidig, R. E., and Snyder, R. S.
1929. The cause of low productivity in recently cleared coniferous timber lands. Proc. & Pap. First Int. Congr. Soil Sci. 3: 1-17.

Pennypacker, S. P., Sopper, W. E., and Kardos, L. T.
1967. Renovation of wastewater effluent by irrigation of forest land. J. Water Pollut. Contr. Federation 39(2): 285-296.

Pew, J. C.
1967. Lignin: an inviting storehouse. Agr. Sci. Rev. 5(4): 1-8, 28, illus.

Pokorny, F. A.
1966. Pine bark as an organic amendment in production of container plants. Georgia Agr. Res. 7(4): 8-9.

__________ and Gugino, J.
1967. Comparison of potting media for herbaceous pot plants. Georgia Agr. Res. 9(2): 3-4.

__________ and Perkins, H. F.
1967. Utilization of milled pine bark for propagating woody ornamental plants. Forest Prod. J. 17(8): 43-48, illus.

Richards, S. J., Warneke, J. E., Marsh, A. W., and Aljibury, F. K.
1964. Physical properties of soil mixes. Soil Sci. 98(2): 129-132, illus.

Roberts, A. N.
1968. Mulches in maintenance planning. Oreg. Ornamental Short Course Sess. for Landscape Gard., Oreg. State Univ., 12 pp.

__________ and Mellenthin, W. M.
1959. Effects of sawdust mulches. II. Horticultural crops. Oreg. Agr. Exp. Sta. Tech. Bull. 50, 34 pp.

Schreiner, O., and Shorey, E. C.
1909. The isolation of harmful organic substances from soil. Bur. Soils Bull. 53, 53 pp., illus.

Sheridan, E. T., and De Carlo, J. A.
1957. Peat in the United States. U. S. Bur. Mines Inform. Circ. 7799, 25 pp., illus.

Shrikhande, J. G.
1940. Effect of narrow carbon-nitrogen ratio and of naturally occurring tannins in decomposing plant materials upon the production of mucus. Soil Sci. 49: 1-8.

Smith, J. H., Carter, D. L., Brown, M. J., and Douglas, C. L.
1968. Differences in chemical composition of plant sample fractions resulting from grinding and screening. Agron. J. 60(2): 149-151.

Sundman, V.
1961. Experiments with bacterial degradation of lignin. Paperi ja Puu 43: 673-676, illus.

____
1964a. The ability of conidendrin-decomposing Agrobacterium strains to utilize other lignans and lignin-related compounds. J. Gen. Microbiol. 36: 185-201, illus.

____
1964b. A description of some lignanolytic soil bacteria and their ability to oxidize simple phenolic compounds. J. Gen. Microbiol. 36: 171-183, illus.

__________, Kuusi, T., Kuhanen, S., and Carlberg, G.
1964. Microbial decomposition of lignins. IV. Decomposition of lignin by various micro-populations. Acta Agr. Scand. 14: 229-248.

Taylor, S. A.
1965. Water in the soil is different. Farm & Home Sci. 26(1): 18-19, 25.

Toussoun, T. A., Weinhold, A. R., Linderman, R. G., and Patrick, Z. A.
1968. Nature of phytotoxic substances produced during plant residue decomposition in soil. Phytopathology 58(1): 41-45, illus.

Williams, A. H.
1963. Enzyme inhibition by phenolic compounds. *In* Enzyme chemistry of phenolic compounds, J. B. Pridham (ed.), chapter 9, pp. 87-95. Oxford: Pergamon Press. (Distributed by Macmillan Co., N.Y.)

Bollen, W. B.

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